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NRL Report 5756

SPACE SURVEILLANCE SYSTEM - TECHNICAL SUMMARY REPORT NO. 5

[UNCLASSIFIED TITLE]

Applications Research Division

March 1, 1962

U. S. NAVAL RESEARCH LABORATORY
Washington, D.C.

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CONTENTS

ABSTRACT
[Confidential]

The U.S. Navy Space Surveillance System now comprises seven stations on a great circle path across the Southern United States. Activation of the central 560-kw transmitter in June 1961 and narrowband receiving equipment at all four receiver sites has greatly increased the system capability. Currently, the system makes about 700 observations per day and produces orbital elements on over 100 different orbiting objects.

Initial orbital elements obtained from the first satellite pass through the system are based on position, determined by triangulation from two or more receiver stations, and velocity derived by measuring rate of change of phase between the two antennas of a long-baseline interferometer. These data are expected to determine the period to within 5 percent and inclination to 0.5 degree when baselines of one-mile length are completed. The elements are refined in three further steps: two successive passes, passes from the two sides of the orbit, and finally by a differential correction computer program using several days of observations. This final refinement produces the system output in terms of orbital elements usable for any location around the world. They are routinely used to predict future passes of known satellites through the line. Their accuracy is such that currently the passage of stable satellites can be predicted to within one second in time for a week in advance.

Development of automatic data processing using digital techniques is progressing satisfactorily. This system is expected to be operating in the summer of 1962. It will use an IBM 7090 computer on line to produce orbital elements within seconds of the satellite pass through the system. The system capacity will be limited only by computing time and is initially being programmed for a population of about 1500 satellites. Planned extensions and refinements permit handling up to 10,000 satellites before requiring a new higher speed computer.

PROBLEM STATUS

This is the fifth Technical Summary Report providing the current status of the System Development; work is continuing.

AUTHORIZATION

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BuWep TASK No. CARD 00030/5661 S434-00-000

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SPACE SURVEILLANCE SYSTEM
TECHNICAL SUMMARY REPORT NO. 5
[Unclassified Title]

BACKGROUND

Under sponsorship of ARPA, the U.S. Naval Research Laboratory initiated a program in June 1958 to develop, install, and operate the Space Surveillance System for the detection, tracking, and orbit prediction of nonradiating satellites. Operation of experimental units on a 24-hour-per-day basis began in February 1959. Responsibility for the system was transferred to the Department of the Navy in October 1960, and management control was assigned to the Bureau of Naval Weapons. Operational control of the Space Detection and Tracking System (SPADATS) was assigned in October 1960 to the Commander-in-Chief, North American Air Defense Command (NORAD). The Navy maintains and operates the U.S. Naval Space Surveillance System (NAVSPASUR), under a Commanding Officer, at Dahlgren, Virginia to meet both Navy and national requirements as a component of the SPADAT System. Technical direction of further development and improvements is assigned to the U. S. Naval Research Laboratory. This report summarizes the technical status of the system and discusses evaluations describing the current system capability.

Detection and tracking stations are located along a great circle path extending across the Southern United States (Fig. 1). Transmitters along the line radiate a thin vertical fan beam, broad in the east-west direction, to illuminate any satellites crossing the line. A 560-kw transmitter at Kickapoo Lake, Texas, provides the major illumination, supplemented by 50-kw transmitters at Gila River, New Mexico, and Jordan Lake, Alabama. Reflections from objects passing through the beam are picked up at receiver sites, distributed along the great circle line, whose antennas have a similar beam shape. At the receiving stations interferometer techniques are employed to provide data for accurate computation of angle of arrival. Receiver output data is transmitted over telephone lines to an Operations Center at Dahlgren, Virginia, for recording and processing. The recorded data provide (a) time of passage through the beam, (b) signal level and shape, and (c) electrical phase angles between the signals from pairs of antennas having various baselines. After manual preparation, the data is processed by a digital computer to provide zenith angles of the observations, to determine orbital elements, and to produce future position predictions for the various satellites continually under observation. Observations and orbital elements are reported over a private cryptoteletype line to NORAD/SPADATS at Colorado Springs, Colorado. Further background information may be found in a summary report[1] and in discussions of system extensions[2].

STATUS

Transmitting Stations

The transmitter station at Kickapoo Lake began 24-hour-a-day operation in June 1961. After a shakedown period, it has averaged 99.75 percent on-the-air time.

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[1] "The Space Surveillance System," NRL Report 5575, Oct. 1960.

[2] "An Advanced Space Surveillance System," NRL Memo. Report 1147, Feb. 1961.

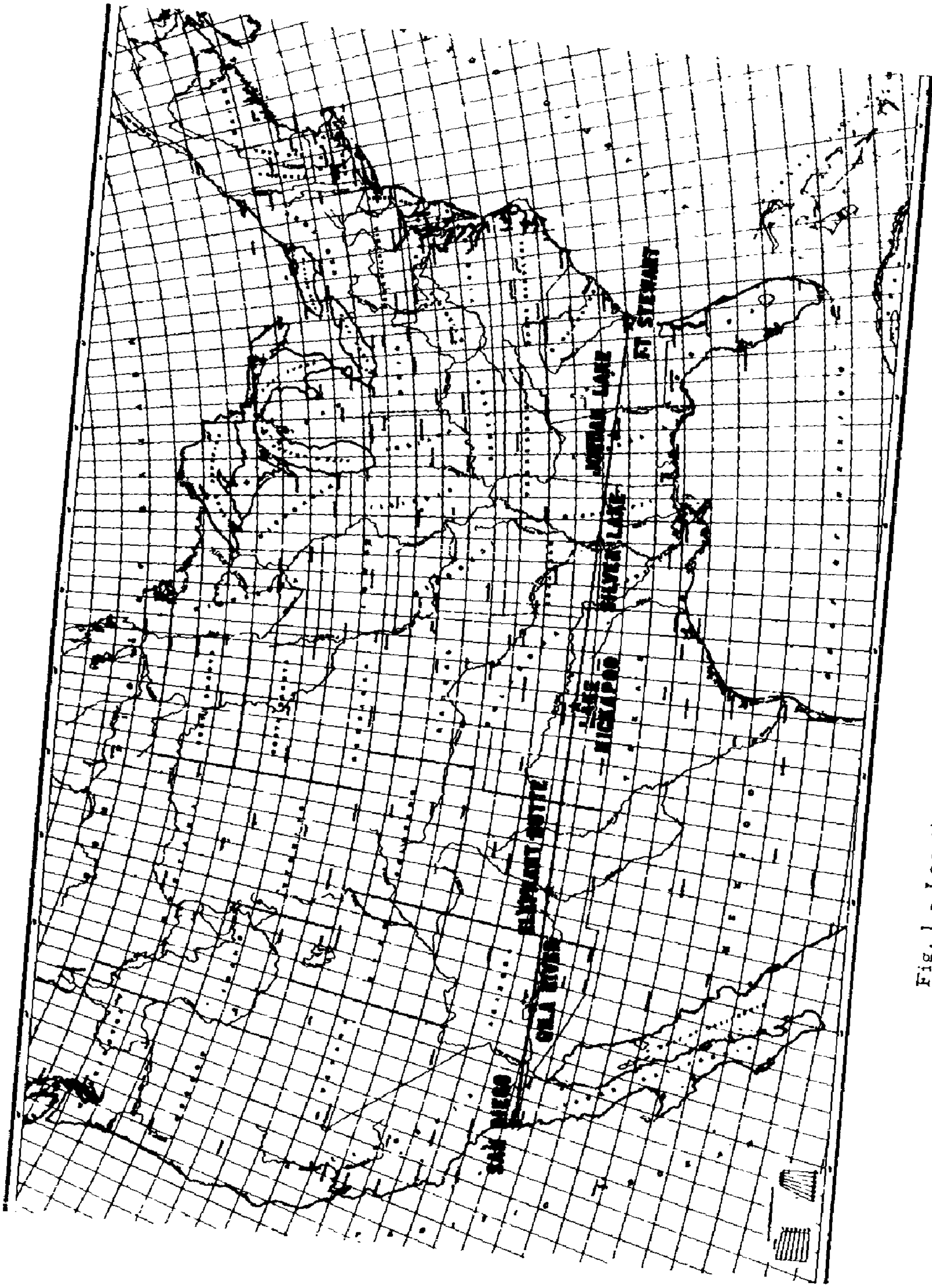

Fig. 1 - Location of the Space Surveillance Stations

The 3-1/8-in. styroflex transmission line at Gila River was replaced by rigid line in June 1961 because of tape spiral disintegration under the extreme temperatures. Later, both high-voltage transformers burned out and were rewound for higher temperature operation. This station is now in good operating condition.

The Jordan Lake transmitter was overhauled in June 1961. A failure of the styroflex line at this station also occurred and portions were replaced by rigid line in January 1962. This transmitter is an experimental unit whose components are 10 years old, requiring considerable maintenance. At some future date when the frequency of operation is changed, replacement is recommended, with the beam reoriented to improve coverage at low heights.

The Kickapoo Lake station uses a one-mile-long antenna producing a N-S beam width of about 0.1 degree. The small transmitter antennas are 1600 feet long with a N-S beamwidth of about 0.3 degree. The E-W beamwidths are wide, covering about 130 degrees. All transmitting antennas are linearly polarized, with the electric vector in the E-W direction.

Receiving Stations

Modifications have been made at all receiving stations. Fort Stewart continues to be used for new R and D items and differs from the other stations in many respects. All receiving antennas are collinear, with the plane of polarization rotated 90 degrees with respect to the transmitter antennas.

Baselines have been modified at San Diego, Elephant Butte, and Silver Lake. The configuration of these stations is shown in Fig. 2. Minor shifts were made during the period between June and August 1961 (at which time narrowband receivers were also installed) to permit combining phase channels to reduce the data line requirements. Additional antennas are being installed to provide E-W baselines up to 5200 feet which will (a) furnish phase-rate data for velocity computation and (b) increase the equipment capability for determining zenith angles to 0.01 degree. Each of the four antennas giving baselines from 1040 feet upward (see Fig. 2) consist of 48 five-element yagi arrays, while the original antennas are dipoles above a common ground screen. One collinear antenna was extended to 1600 feet to provide a higher gain detection antenna, utilized in the "alert" system, and also to provide a N-S baseline up to 1200 feet. The remaining antennas at the three standard sites are 400 feet in length. The long-baseline antennas are only partially installed at this time and are not yet operational at any station.

The Fort Stewart antenna system spacings have not been changed from those reported in Technical Summary Report No. 4. The collinear phase antennas are 1600 feet long and have been used operationally, though they will not be fully effective until the higher gain alert antenna is installed. The alert antenna will be compatible with the existing long antennas. An east-west baseline of 5200 feet is also to be provided. The initial phase-rate-evaluation antennas remain to provide baselines of 1851 feet in both the E-W and N-S directions.

Frequency

Because several U. S. satellites carry solar-powered transmitters operating at a frequency of 108.00 Mc, these satellites transmit to the space surveillance receivers even when well out on the antenna side lobes. This resulted in unnecessarily long signal durations. Effective December 28, 1961, the operating frequency was changed to 108.015 Mc which reduces the duration of the longest radiating response.

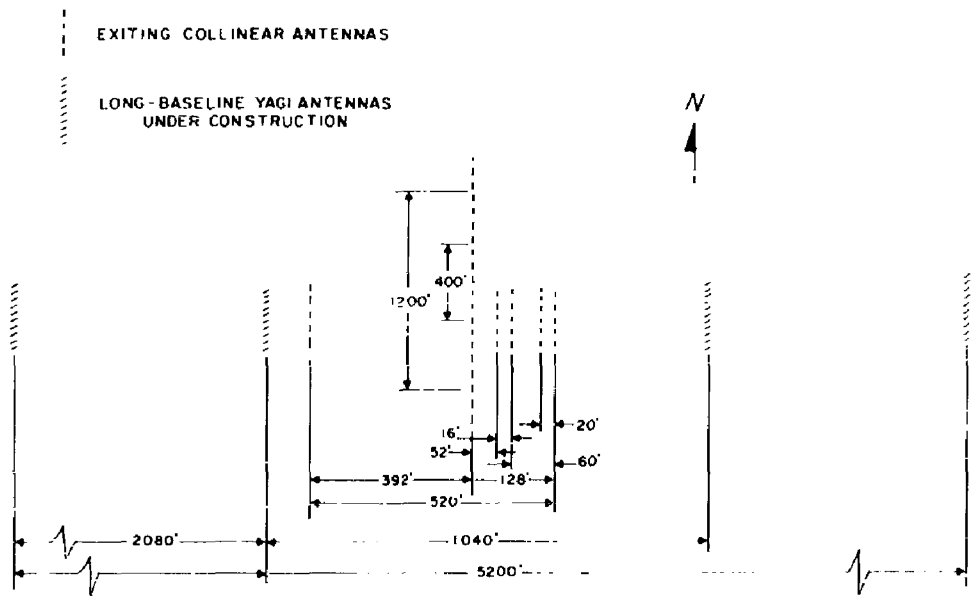

Fig. 2 - Configuration of the Modified E-W Baselines at San Diego, Elephant Butte, and Silver Lake

Because of only temporary authorization to operate at 108 Mc, a permanent frequency band has been chosen in the region of 150 Mc. New installations will be designed with such a move in mind. For example, new antennas are being broadbanded to cover both 108 and 150 Mc.

EQUIPMENT

Kickapoo Lake Transmitter

The large central transmitter at Kickapoo Lake, Texas, although operating around the clock since June 1961, has undergone shakedown and completion of miscellaneous items during the past few months and can be considered essentially completed. This installation consists of a 9-bay antenna (Fig. 3), one mile long, whose north-south beam width is about 0.1 degree. Each antenna bay is driven by a final amplifier with all bays locked in phase (Fig. 4). Any of the nine units may be inactivated for maintenance without affecting the operation of the remainder of the system. The amplifier for the center antenna bay serves as a back-up driver for the system. These arrangements provide high reliability for nearly full power operation without expensive duplication of equipment. With all components operating, 560 kw of cw power is produced at the system frequency of 108 Mc.

Narrowband Receivers

Improvements have been made at all receiving stations with the installation of the "alert" system consisting of an i-f preselector using a comb filter to reduce the system bandwidth to 100 cycles. One-hundred-sixty channels provide a total bandwidth of 16 kc

required to cover the doppler-shifter signals. A high-gain detection antenna operates with the i-f preselector to give about 19 db improvement in system sensitivity. Using the comb filter to select the local oscillator frequency permits a tuning to the doppler frequency so that the phase receivers may also be narrowband (Fig. 5).

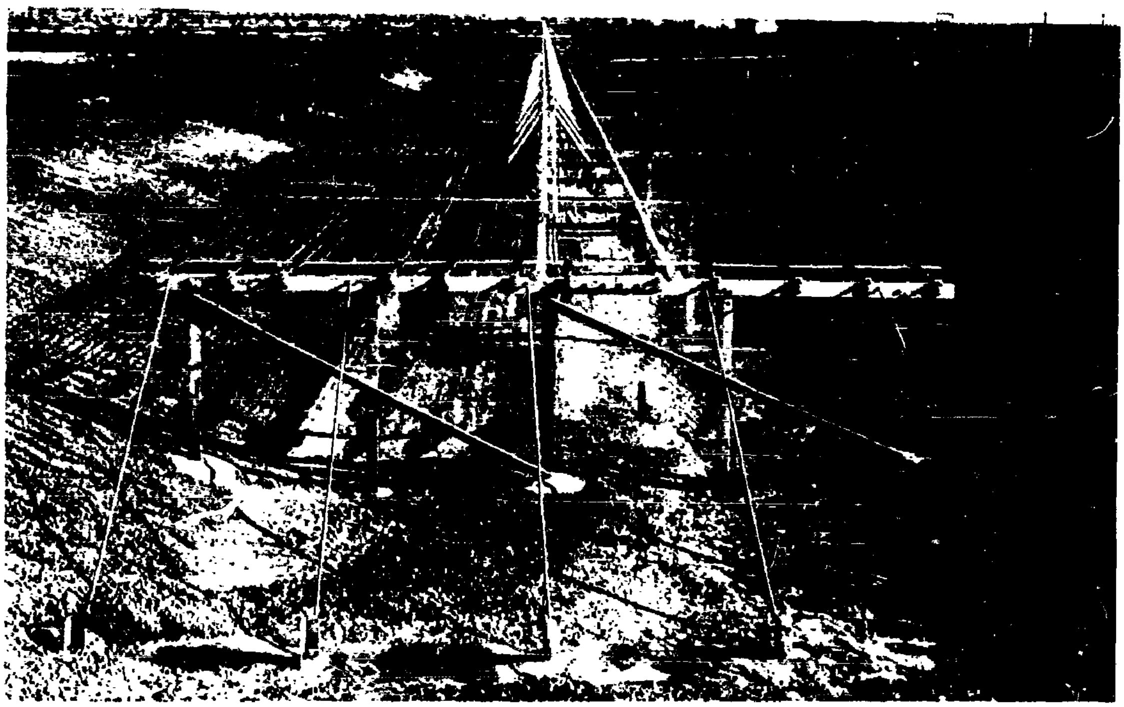

Fig. 3 - The mile-long transmitter antenna at Lake Kickapoo, Texas

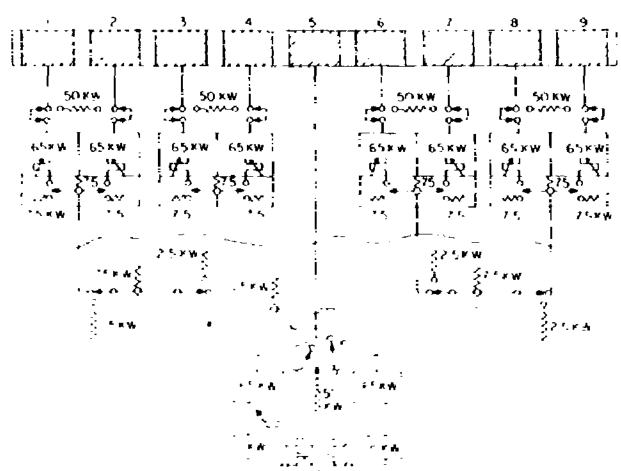

Fig. 4 - Block diagram of 560-kw transmitter at Lake Kickapoo

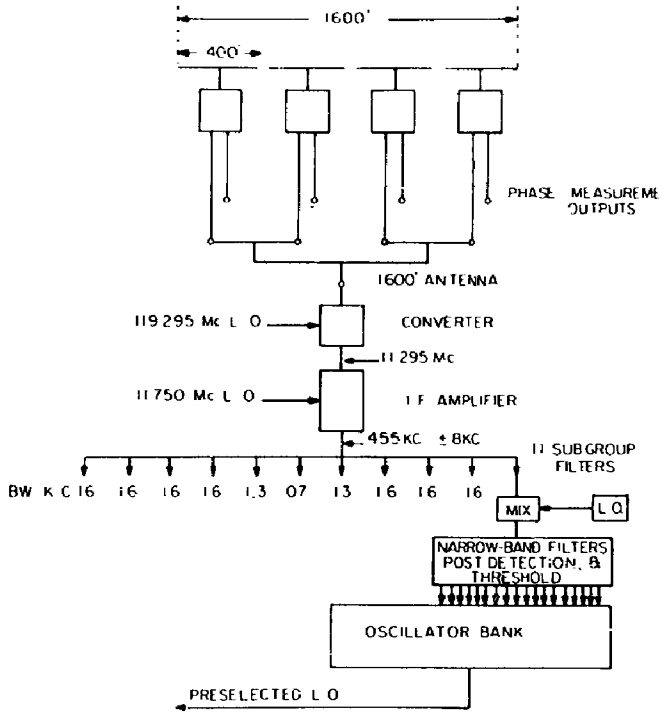

Fig. 5 - Method of increasing the sensitivity using an "alert" system

Figure 6 is a photograph of the Sanborn record comparing this narrowband receiver with a wideband receiver. The Explorer I satellite is received on narrowband but there is no indication on the wideband.

In addition to increasing the system sensitivity this equipment provides an alert signal which may be used to start a recorder or to initiate other actions at the beginning of a signal. Two post-detection filter bandwidths are available in this system and are automatically selected by rate of signal build up. A 0.7-cycle filter is connected in the circuit except when a strong signal, determined by rate of signal build up, switches to the 14-cycle filter. This provides the highest sensitivity for the weaker more distant signals but widens the bandwidth for nearby objects, whose reflected signals are of less duration because of the shorter time in the antenna beam. This adjustment of bandwidth compensates to some degree for the signal decrease with fourth power of range that all radar systems encounter.

The narrowband system is less sensitive to interference from radio stars and the sun. Figure 7 compares the wideband and narrowband systems at a time of solar interference.

Digital Data Processing

A digital system for automatic data processing is being developed. Plans are for this system to be operating in the summer of 1962. The output signals will be converted to digital form at the receiving stations for transmission over leased telephone data lines (similar to voice communication facilities) to a central processor at the Space Surveillance Operations Center, Dahlgren, Virginia.

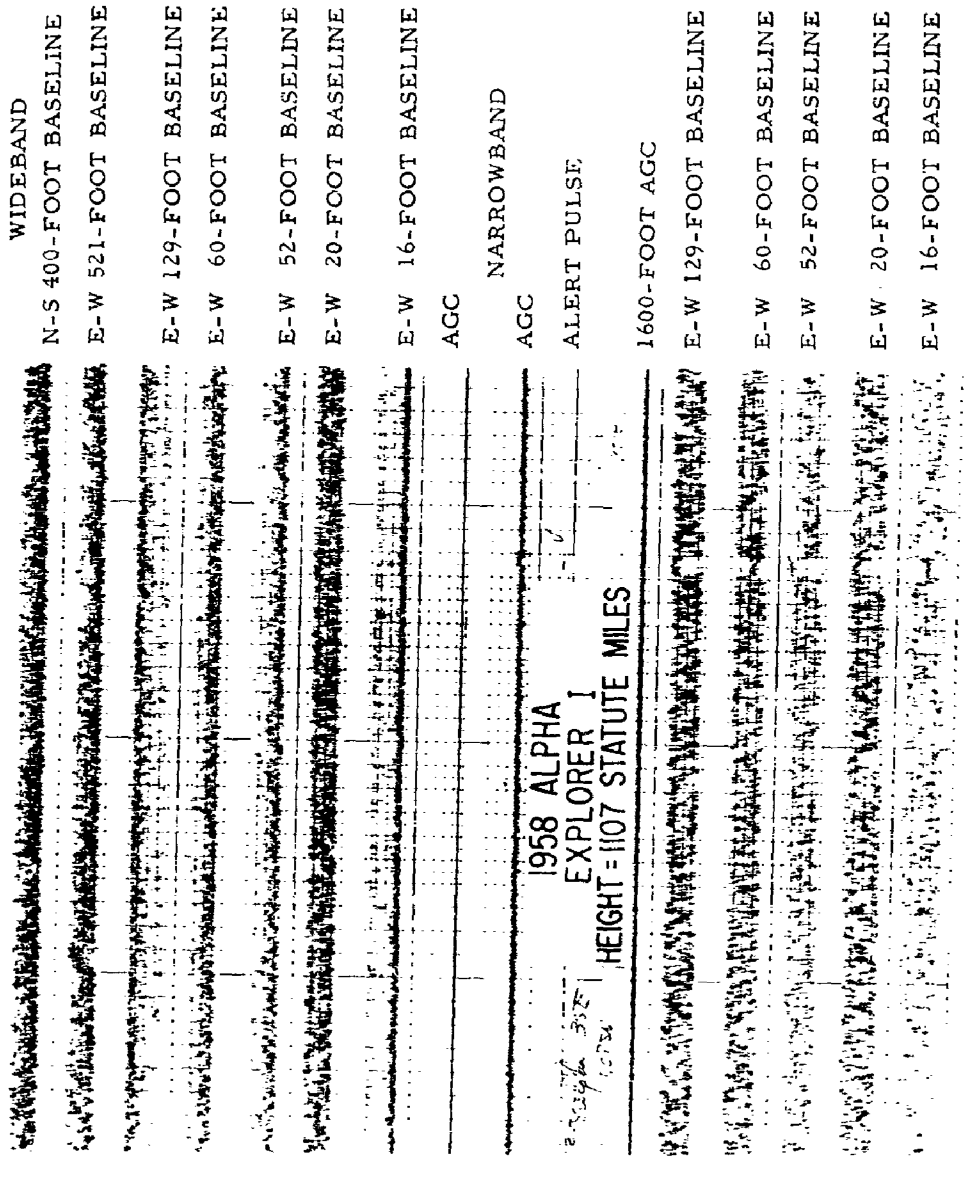

Fig. 6 - Comparison of narrowband prototype receiver with wideband receiver for Explorer I

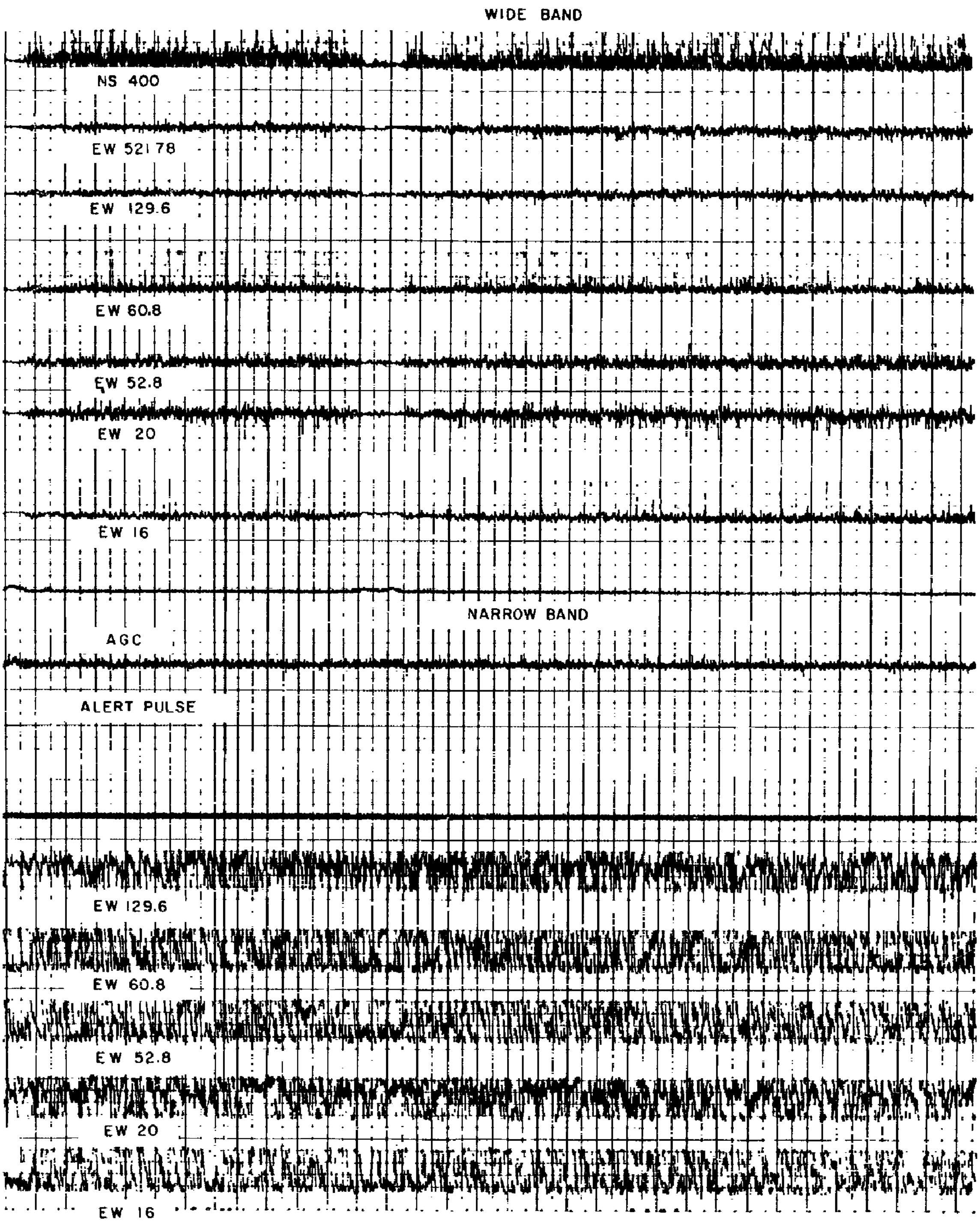

Fig. 7 - Passage of the sun through the antenna beam, recorded on a wideband and a narrowband system to demonstrate the negligible phase quieting in the narrowband system. The letters and numbers to the left indicate channel numbers.

The processing will be performed by an on-line IBM 7090 computer coupled to the system through the Automatic Digital Data Assembly System (ADDAS) together with standard auxiliary equipment for data storage and print out. A second 7090 computer will be available as back up and will be used during maintenance and outage periods to continue essentially real-time processing.

The system is being designed to process completely the data needed to produce a rough orbit within about five seconds after passage of the satellite through the SPASUR beam. This includes the capability of providing look angles for specific locations within the surveillance area of other detection and tracking components.

Initially, equipment is being provided to process all signals received by the four receiving stations. The design permits expansions to 10 master receiving stations by adding unitized components and ultimately to 15 master receiving stations with limited modifications. The presently planned computing capacity (using one 7090 computer at a time) is sufficient to completely process all signals from four receiver sites and differentially correct orbital elements once a week on about 1500 satellites. About 2 percent of the time would be spent processing noise. A greater computer capacity is attainable in operation since orbit improvement need not be done weekly on many satellites - perhaps on the majority - assuming the population will be built up by long-lived objects whose orbits are by their very nature stable. The differential correction and tape access procedures consume most of the time in the processing program. The latter may be decreased by adding a disk file now under consideration. Also, complete processing of all observations is unnecessary; only enough to provide accurate updated orbital elements need be processed for old known satellites. One 7090 computer system may thus be programmed to cope with 4000 to 5000 satellites. Should this capacity be reached, the back-up computer could be brought in to assist on up to 8,000 to 10,000 satellites. Beyond this point one would expect to use some new higher speed computer. Estimates of processing times are listed in Table 1.

Table 1
Data Processing Times for Four Receiving Stations

Data Processed or Computer Operation	Time (hrs/wk)
Noise	2.4
Fixed-Output Summaries	1.1
Input Data Processing	0.01/satellite
Correlation	0.01/satellite
Differential Correction	0.04/satellite
Predictions	0.01/satellite
Tape Access	0.04/satellite
Output	0.01/satellite

Detection of a new satellite is achieved when the system makes an observation which has characteristics not identifiable with a known object. The orbits of all known satellites will be maintained in a computer catalog and "gate" predictions made. If a signal falls within the gate it will be assigned to the proper known orbit. The system will gate (a) time of passage, (b) zenith angle, and (c) phase rate if needed. Other information is available, such as doppler shift, and is useful for identifying certain nonsatellite signals. Plans do not call for its use as a routine, but it will be stored for analysis in a problem situation. The more precise the orbital elements, the tighter the gates can be, and thus the fewer problem observations to be referred to the system operator for further analysis.

Equipment is being developed for evaluation which will analyze the signal pattern at the individual receiver sites and make a determination as to its probable type - satellite, meteor trail, noise, etc. If found desirable, a pattern Recognition Technique (PRT) code will be transmitted with each signal designating this determination. No signals would be eliminated at the station as the data line has enough capacity to transmit all data, including noise, but the PRT code can be useful in processing by the computer. The techniques relate to the measurement of signal symmetry, signal shape, and frequency content.

The primary output of the automatic system is the orbital elements. These will be routinely produced on known satellites and printed out in standard format. If a new object enters the system, a flash message will be automatically sent to NORAD/SPADATS immediately and printed out locally, giving in addition to its orbital elements as much information as is available, such as the individual station readings. Information will also be printed out locally about satellites which require special attention and when trouble is encountered.

Certain fixed outputs needed for supervisory control of the system are to be produced. These include (a) an hourly report summarizing the events occurring during the preceding hour, (b) a daily summary for the previous 24 hours, (c) a 24-hour prediction list generated once a day, and (d) a calibration log at the end of each day.

In addition, outputs will be produced on request, giving sets of elements by individual or class of satellites, individual satellite predictions, ephemerides, or observations.

CALIBRATION

Cameras at all receiving stations permit calibration by comparing the optical position of satellites, with reference to the star background, with the position obtained using interferometer measurements. At present all stations are calibrated to within an error equivalent to 0.1 degree at zenith.

With the addition of 5200-foot baselines the measurement precision will be increased until the variability in ionospheric refraction will be a serious factor. A prototype system is being implemented to provide corrections for this effect at frequent times during the day.

A 400-Mc beacon is being placed in orbit, attached to large final-stage rockets. This beacon will trigger as it passes over the surveillance line by reception of the 108-Mc frequency. A ground system will provide for comparative measurements on the two frequencies so that the ionospheric effect can be accurately determined. The 400-Mc system will be calibrated optically using the large rocket body. Additional beacons carried on suitable launches will provide frequent calibrations as required by the changing ionospheric conditions.

SYSTEM SENSITIVITY

The system is now operating at the full range capability for which the design has been funded. The major recent contributions have been in the new central transmitter delivering 560 kw into a mile-long antenna and the narrowband i-f preselectors installed at the receiving stations. The Kickapoo transmitter provides a gain of 30 over the small 50-kw transmitters with their lower gain antennas, and the receiver improvements provide a gain of about 100. Figure 8 shows the contours of equal probability for observing objects of one-square-meter radar cross section at two or more receiving stations and for the system as now operating.

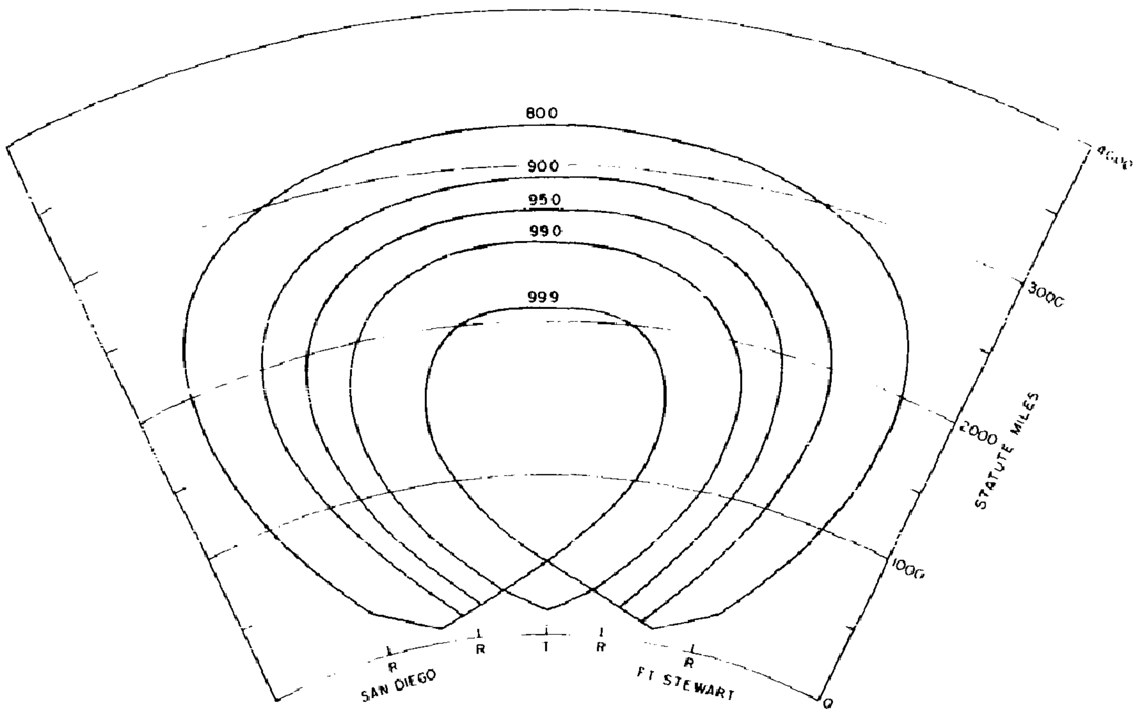

Fig. 8 - Observational probability vs coverage for present system (radar cross section = 1 square meter)

This marked increase in sensitivity has been reflected in the greatly increased number of satellite observations, as shown in Table 2 for the months preceding, during, and after the modification period. The satellites previously observed are now observed more often – most of them to apogee – and more objects are seen, such as de-spin weights, covers, and pieces left in orbit.

The design range of 2500 miles on one-square-meter objects has been realized. With the increased sensitivity it is possible to observe 1958 Beta 2 (Vanguard I) at apogee. During the period this satellite was near perigee over the system, the received signal strength was measured and used to calculate the effective radar cross section. Better calibration was possible with these stronger signals than for earlier observations.

Table 2
Number of Satellite Observations (Reflected Signals Only)
Reported by Month

Date	No. of Reflected Signal Observations	No. of Passes	Average No. of Observations per Pass	No. of Satellites for these Observations
Jan. 1961	1966	1149	1.70	20
Feb. 1961	2251	1327	1.70	31
Mar. 1961	2460	1971	1.68	25
Apr. 1961	2524	1499	1.68	31
May 1961	3023	1742	1.74	38
June 1961	6165	3073	2.01	52
July 1961	13,648	6743	2.02	107*
Aug. 1961	14,389	7222	1.99	113*
Sept. 1961	17,124	8039	2.13	110*
Oct. 1961	18,374	8829	2.08	108*
Nov. 1961	19,872	9210	2.16	113*
Dec. 1961	20,903	10,017	2.09	118*

*These numbers have been adjusted to include 54 fragments of 1961 Omicron.

The mean of 20 observations was about 1.0 ft.^{2} and the rms deviation of the log-normal distribution was 4.3 db. This area is somewhat less than had previously been calculated. All of these measurements were taken while the satellite was in darkness and, thus, its solar-powered transmitter inactive. It is believed the previous observations included some radiated signal in the wideband AGC (which is used for signal strength measurement) because of the small separation of the reflected and radiating frequencies.

During the period when 1958 Beta 2 was near apogee (2470 statute miles), observations were made with the new i-f preselectors operating, resulting in a signal being received at the station about 50 percent of the time. These experimental results verify the design calculations.

The system noise temperature has been determined by measuring the calibration signals necessary to trigger the alert system. This signal averaged over 24 hours at the western receiver stations to -143 dbm, corresponding to a system noise temperature of 2500°K. The accuracy of these measurements is estimated as ±1.0 db

ORBIT CALCULATIONS

Accurate orbits must be maintained on all known satellites so that observations on these satellites will be recognized. These elements constitute the major output of the system. In addition to their use to feed back into the system to make recognition of

a newly detected object possible, these elements are available for other purposes where predictions of satellite motion is required. For these calculations observations routinely collected over an extended period of time are used in a differential correction computer program to provide the best possible accuracy. When a new object enters the system elements must be calculated on the data available, which may be restricted to a single pass. Then as more data are obtained the calculations are refined. Programs are provided for four levels of data input.

Single-Pass Orbits

Initial data on a new object resulting from a single pass provides position of the satellite at the time of penetrating the East-West fan beam. This position is fixed by the intersection of the directions measured from two or more receiver stations. The current angular accuracy of about ±0.1 degree will be increased to ±0.01 degree for optimum passes for the 5200-foot baselines being installed. In addition to determining position, the rate of change of phase in the long baselines is also measured which provides enough measurements to establish an orbit. These latter measurements can be made to within about 5 percent on the 5200-foot baselines.

The sensitivity of orbital elements to variations in these input data is illustrated by Table 4 where calculations were made for two different passes of "Echo" through the system. One pass was approximately midway between the two receiving sites making the observation and the other pass was west of both sites. The variation of period and of inclination are tabulated, being perhaps the two most important elements to establish first. The time of observation, observed angles, and the calculated periods and inclinations are given in Table 3.

Table 3
Input Data for Two Passes of "Echo" Through the SPASUR System

Input Data	Observation "A"*	Observation "B"†
Date	9-3-61	10-3-61
Time	$19^h\ 12^m\ 32.4^s$	$17^h\ 26^m\ 55.0^s$
San Diego angle	21.4°W	23.1°E
Elephant Butte angle	54.7°W	21.7 W
Calculated period	115.980^m	120.676^m
Calculated inclination	48.276°	46.576°

*"Echo" passed west of both sites (unsymmetrical pass).

†"Echo" passed approx. midway between both sites (symmetrical pass).

Table 4
Illustrating the Sensitivity of Orbital Elements to Variations in the Input Data for Two Different Passes of "Echo" through the System

Station	Quantity Varied	Amount of Variation	Observation "A" (unsymmetrical)		Observation "B" (symmetrical)	
			Period Variation (percent)	Inclination Variation (degrees)	Period Variation (percent)	Inclination Variation (degrees)
Elephant Butte	E-W angle	0.1°	-2.3	+0.052	-0.9	-0.008
		0.3°	-6.4	+0.158	-2.6	-0.023
		1.0°	-18.0	+0.537	-8.0	-0.074
San Diego	E-W angle	0.1°	+1.5	-0.018	-1.0	-0.010
		0.3°	+4.7	-0.055	-2.9	-0.028
		1.0°	+18.5	-0.193	-9.0	-0.104
Elephant Butte	E-W angle rate	2%	-2.0	+0.174	+2.2	-0.181
		5%	-4.3	+0.441	+5.9	-0.445
		10%	-6.7	+0.907	+13.6	-0.874
Elephant Butte	E-W angle rate	-2%	+2.3	-0.171	-1.9	+0.183
		-5%	+6.5	-0.421	-4.6	+0.461
		-10%	+16.2	-0.826	-7.6	+0.940
San Diego	E-W angle rate	2%	+7.4	-0.468	+1.5	-0.159
		5%	+21.3	-1.122	+4.0	-0.396
		10%	+57.4	-2.116	+9.5	-0.778
Elephant Butte	N-S angle	0.1°	-1.0	-0.007	+0.2	+0.021
		0.3°	-2.8	-0.019	+0.6	+0.064
		1.0°	-8.8	-0.060	+2.0	+0.211
San Diego	N-S angle	0.1°	+1.2	-0.018	-0.1	-0.001
		0.3°	+3.7	-0.054	-0.4	-0.004
		1.0°	+14.2	-0.181	-1.2	-0.013
Elephant Butte	N-S angle rate	2%	+1.4	+0.338	+2.8	+0.369
		5%	+3.6	+0.852	+7.5	+0.919
		10%	+7.7	+1.695	+16.3	+1.815

The system capability, with the long baselines, for an average satellite is estimated to be about 5 percent in period and 0.5 degree in inclination for single passes in a favorable position. Table 5 compares the single-pass elements with established elements for two satellites, using observations taken with existing equipment which has somewhat less capability than that now being installed.

Two-Point Orbits – Successive Passes

Many satellites are first observed in the eastern portion of the system and then again, one period later, in the western portion, thus giving observations on two successive passes. A much improved value of the period can thus be established giving an improved semimajor axis. Most other elements are appreciably better than those for a

Table 5
Orbital Elements Calculated from Data on Only One Satellite Pass Compared with the Same Elements Calculated on the Basis of Several Days of Data (Differential Correction Program)

Satellite and Type of Signal: Observing Stations and Zenith Angle:	60 Beta 2 (Radiated) Ft. Stewart 2.60°E Silver Lake 58.70°E		59 Eta 1 (Reflected) Elephant Butte 16.05°E San Diego 69.96°E	
Orbital Element	Single Pass 9-15-61	Diff. Cor. (NAVSPASUR)	Single Pass 9-15-61	Diff. Cor. (NAVSPASUR)
Anom. Period (min.)	102.75	99.209	139.73	129.922
Semimajor axis (stat. mi.)	4515.44	4411.18	5542.60	5280.17
Inclination (deg.)	48.373	48.372	33.339	33.341
Eccentricity	0.0312	0.00395	0.2428	0.19047
Rt. Ascension (deg.)	356.646	356.541	5.635	4.642
Perigee (stat. mi.)	411.0	430.4	233.2	311.0
Apogee (stat. mi.)	693.1	465.2	2925.3	2322.5

NOTE: Phase rate was obtained from 400-foot N-S baselines and 520-foot E-W baselines, except for Fort Stewart where 1851-foot baselines were used.

single pass. The argument of perigee and eccentricity are still not very well defined since such a small part of the orbit is observed on successive passes. Table 6 presents NAVSPASUR data on five satellites of varying parameters showing the elements for two-point orbits, elements for differentially corrected orbits, and their differences. It will be noted that the latitude difference between successive passes ranges only up to 2.59 degrees.

Two-Point Orbits – Opposite Sides

After about 12 hours the rotation of the earth will bring the surveillance system under the opposite side of the satellite orbit. With two such observations spaced far apart around the orbit, very good elements are possible. Table 7 compares the elements thus obtained with elements independently produced by NASA using Minitrack data.

Differentially Corrected Orbits

The final refinement is made using several observations, up to several days, in a differential correction computer program. Evaluation of these elements has been made in several ways. First they are used in the system to predict for several days (or sometimes weeks) in advance the time and place of passage of the known satellites through the line. The predictions must be corrected more frequently for low and decaying satellites than for those having less drag. An indication of how good the elements are is given by comparing these predictions with observations at future times. Table 8 gives the statistics for the first week in December 1961, considering a typical period, where the time between making the prediction and the observation was 6 days for the 105 satellites being observed by the system.

Table 6
Calculated Orbital Elements for Five Different Satellites Using Two Successive Passes Compared with the Differentially Corrected (D.C.) Elements Obtained from Several Days of Data

Orbital Element	Method of Calculation and Difference	1961 Alpha I SAMOS II	1961 Delta 2 Explorer IX Final Stage	1961 Rho 2 Tiros III Final Stage	1961 Alpha Epsilon I Discoverer XXXIV	1961 Alpha Eta 1 Transit IV B
Epoch (yr mo da / hr min sec)		620111 063509.0	620102 151656.8	620105 032523.0	620111 104350.0	611219 071642.4
Incli-nation (deg)	2 points	99.22	38.35	48.22	84.29	32.43
	D.C.	97.41	38.85	47.88	82.51	32.43
	Diff.	1.81	-0.50	0 34	1.78	0.00
Perigee Ht. (stat. mi.)	2 point	249.3	414.2	432.1	184.8	616.3
	D.C.	288.1	397.3	456.8	154.2	594.9
	Diff.	-38.8	16.9	-24.7	30 6	21.4
Apogee Ht. (stat. mi.)	2 point	395.3	1611.2	546.8	543.8	683.6
	D.C.	345.9	1610.7	507.2	564.7	686.4
	Diff.	49.4	0.5	39.6	-20.9	-2.8
Anom. Period (min)	2 point	94.832	118.557	100.356	96.234	105.790
	D.C.	94.829	118.552	100.365	96.241	105.784
	Diff.	0.003	0.005	-0.009	-0.007	0 006
R.A. of Node (deg)	2 point	110 340	90.369	266.615	346.135	22 895
	D.C.	109.190	89.037	267.155	347.347	22 950
	Diff	1.150	1.332	-0.540	-1.212	-0.055
Arg. of Perigee (deg)	2 point	109.436	173.008	221.728	331.846	284.935
	D C	73.906	174.616	49.513	289.496	215 426
	Diff	35.530	-1 608	172.215	-42.350	-69.509
Lat. diff. (deg)		1.67	0.58	2.59	0.87	1.61

Table 7
Orbital Elements for 1960 Eta 2 (Solar Radiation)

Orbital Elements	NASA Elements	NRL Elements from Space Surveillance Data				
		1 and 10*	15 and 24	66 and 71	85 and 94	127 and 136
Anom. Period (min)	101.64526	101.645	101.645	101 646	101.645	101.646
Semimajor axis (stat. mi.)	4483.1	4483.1	4483.1	4483.1	4483.09	4483.11
Inclination (deg)	66.769	66.792	66.756	66.579	66.5735	66.6154
Eccentricity	0.03068	0.0302	0.0293	.02999	0.03025	0.03077
Motion of Node (deg/day)	-2.561	-2 565	-2 568	-2.587	-2.588	-2.583
Arg. of Perigee (deg)†	235.321	233.1	228.4	229.2	226.9	229.8
R.A. (deg)	115.771	115.6	113.0	103.9	100.5	92.9
Perigee (stat. mi.)	382	384.2	388.3	385.3	384.1	381.8
Apogee (stat. mi.)	657	655.1	651	654	655	658
		Difference between NRL and NASA Elements				
Anom. Period (min)		0.000	0 000	-0.001	0.000	+0.001
Semimajor axis (stat. mi.)		0.0	0.0	0.0	0.0	0.0
Inclination (deg)		-0.02	-0.01	-0.19	-0.20	-0.15
Eccentricity		-0.0005	-0.001	-0.0007	-0.0004	-0.0001
Motion of Node (deg/day)		0.004	0.007	0.026	0.027	0.002
Arg. of Perigee (deg)†		-2.4	-6.4	-3.1	-4 5	+0.5
R.A. (deg)†		-0 02	-0 06	-0.06	-0.02	+0.06
Perigee (stat. mi.)		2.2	6.2	3.2	2.0	-0.3
Apogee (stat. mi.)		-2 3	-6.3	-3.2	-2.1	+0.3

*Revolution numbers on which observations were made.

†The NASA elements were updated to the epochs of each set of NRL elements to provide a basis for obtaining the difference.

NOTE: Using a radiating satellite, NASA elements were produced from data of the North South Minitrack System using one week of observations to give precise elements. Five sets of elements were computed using Space Surveillance System data limited to the time necessary for the earth to rotate the System under both sides of the orbit. The agreement with NASA elements is indicated by the lower part of the table.

Table 8
Difference Between Predicted and Observed Beam-Crossing Times

Difference	Number of Satellites
One second or less	57
Between 1 and 3 seconds	28
Between 3 and 10 seconds	15
*Greater than 10 seconds	5
	Total: 105

*Maximum difference = 30 seconds.

Further, to show the usefulness of SPASUR elements for any part of the world, other types of comparisons have been made. Table 9 compares elements for 1961 Omicron 1 (Transit IV A) based on independent data. The differentially corrected elements of NAVSPASUR are based on SPASUR signal observations routinely produced. The NWL-TRANSIT elements were produced from Transit doppler data. Each of these two sets of elements were used to compute satellite positions at 10-minute intervals around the orbit. Figure 9 shows the differences of the two computed positions. This difference never exceeded 4 miles and shows no sensitivity to the region of SPASUR line observations. Figure 10 is a similar comparison using NASA elements based on their world-wide network using radiated signals. In this comparison the maximum difference between computed positions was about 1.5 miles.

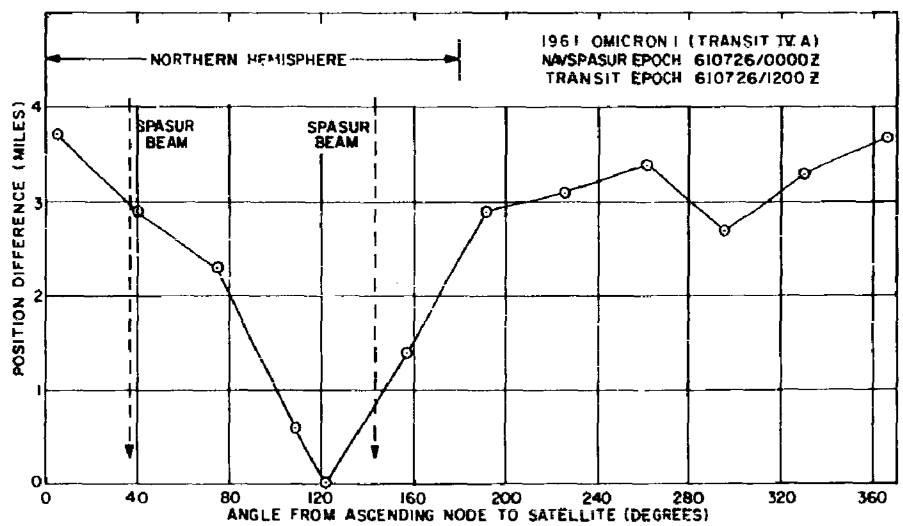

Fig. 9 - Comparison of satellite positions predicted from TRANSIT and SPASUR Orbital Elements

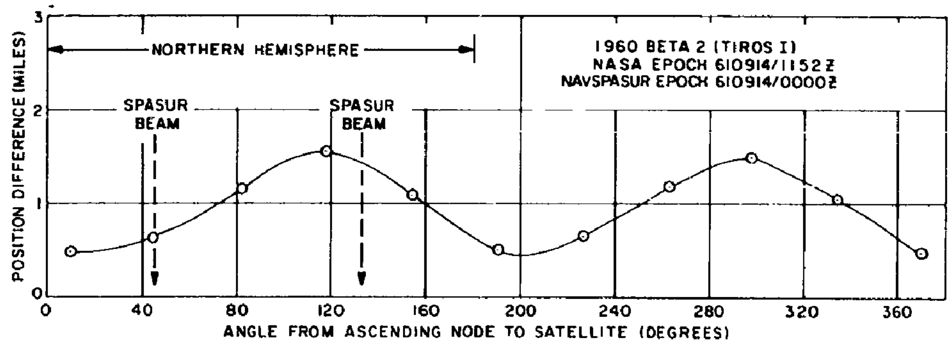

Fig. 10 - Comparison of satellite positions predicted from NASA and SPASUR Orbital Elements

Table 9
Elements on 1961 Omicron 1 (Transit IV A)

Orbital Element	NAVSPASUR	NWL-TRANSIT
Epoch	1961 July 26/000000Z	1961 July 26/000000Z
Anomalistic Period (min.)	103.82301	103.82303
Inclination (deg.)	66.785	66.797
Right Ascension of Ascending Node (deg.)	31.879	31.875
Argument of Perigee (deg.)	277.793	272.471
Eccentricity	0.00775	0.00771
Perigee Height (stat. mi.)	548.3	548.5
Apogee Height (stat. mi.)	618.8	618.5

Comparisons with the NASA and Transit independently produced elements are restricted to satellites radiating to the tracking network used for comparison. A third comparison was made with Smithsonian Astrophysical Observatory (SAO) Baker-Nunn observations. The orbital elements produced from SPASUR reflected signal observations alone were used to predict positions of 1960 Iota 2 (Echo 1, Third Stage) at times which could be observed by the Baker-Nunn stations. The elements used were:

Epoch	8 August 1961/0000Z
Period	118.06152 minutes
Inclination	47.181 degrees
Perigee Height	934.2 statute miles

Apogee Height	1046.3 statute miles
Eccentricity	0.01132
Motion of Node	-3.103
Arg. of Perigee	4.018
R.A. of Asc. Node	218.06152 degrees

The actual observations were obtained from SAO for the period of August 10 to August 17, 1961, and the difference between predicted and observed look angles determined for all 46 observations supplied for this period. Table 10 gives the distribution of these differences showing that none were in error by more than 0.4 degree. This error is about the error of the present SPASUR observations. These stations are widely scattered around the world. These data illustrate that SPASUR elements are satisfactory for making predictions around the world for such purposes as supplying look angles for tracking stations.

Table 10
Difference Between SAO Observed Look Angles and Look Angles Predicted from NAVSPASUR Elements for 41 Observations of 1960 Iota 2.

Difference	Percent
0.1 degree or less	9
0.2 degree or less	59
0.3 degree or less	89
0.4 degree or less	100

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The U. S. Navy Space Surveillance System now comprises seven stations on a great circle path across the Southern United States. Activation of the central 560-kw transmitter in June 1961 and narrowband receiving equipment at all four receiver sites has greatly increased the system capability. Currently, the system makes about 700 observations per day and produces orbital elements on over 100 different orbiting objects. Initial orbital elements obtained from the first satellite pass through the system are based on position, determined by triangulation from two or more receiver stations, and velocity derived by measuring

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